Ventilation performance in cultural centres in Flanders

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ABSTRACT

Ventilation impacts the quality of the indoor environment. Indoor air quality (IAQ) contributes to the overall personal exposure of occupants of a building to certain pollutants and is therefore an important environmental determinant of health. Research shows that European citizens spend on average 90% of their time indoors. The Flemish government, and more specifically the Flemish Department of Environment & Spatial Development, has been conducting research on IAQ in homes and schools to inform and develop policy since 2007. In 2019, the Environment and Health research team at the Flemish Department of Environment & Spatial Development, together with VITO (Flemish Institute for Technological Research) developed a sensor box with innovative and high-quality sensor technology — indoor@box, which allows continuous, real-time measurement of several pollutants and parameters. This makes it possible to communicate results real time, to collect a lot of data over longer periods and to make links with other data (e.g. weather, questionnaires, occupancy rates).

With these indoor@boxes, the Flemish Department of Environment & Spatial Development has been conducting various measurement campaigns in (semi-)public buildings where many people gather or stay, such as schools, sports centres, residential care centres and cultural centres, since 2020. The analysis mainly focuses on CO_2 measurements and ventilation performance. The reports aim at providing concrete advice that considers the specific situation of the building, so that the ventilation improves. In addition, the research gives advice to the policy, which uses existing health guidelines that were important during the COVID-19 pandemic (e.g. in terms of CO_2 values in (semi)public buildings). The research allows to check whether those guidelines are feasible and effective for the different sectors. Ventilation performance can be assessed thanks to a thorough technical screening of the ventilation systems in place.

This paper elaborates on the campaign in ten different cultural centres in Flanders and Brussels, which varied in size, building type, ventilation system and audience capacity (2022). Overall, the cultural centres' ventilation systems are unable to meet the CO_2 guidelines at higher occupancies. The thorough technical screening uncovered that having a ventilation system with sufficient flow rate pulse, in relation to the maximum capacity of the event space does not always guarantee desirable CO_2 values. Additional parameters have an influence, e.g. settings of the ventilation system, activity degree and flow rate per person (m^3/hr/person), composition of the audience, maintenance and management of the system…The combination of CO_2 measurements and technical screenings complement each other well, showing where improvements are needed, and how the ventilation performance can be improved. In the future, the findings from this research could be summarised and incorporated into technical guidelines.

KEYWORDS

public buildings, CO_2 measurements, ventilation performance, policy guidelines, indoor air quality

1 INTRODUCTION

Indoor air quality (IAQ) contributes to the overall personal exposure of occupants of a building to certain pollutants and is therefore an important environmental determinant of health (Superior Health Council, 2017). Research shows that Europeans spend on average 90% of their time indoors (Fernandes et al., 2009). This makes healthy indoor air quality highly important. The performance of (mechanical) ventilation impacts the quality of the indoor environment. By performance, we mean (1) the ventilation effectiveness that indicates how efficiently the airborne pollutant is being removed from the room and (2) how efficiently the fresh air is being distributed in the room through air exchange efficiency (Atkinson et al., 2009). In this research we assessed the performance of the ventilation systems by in depth technical screenings of the systems: we gathered information on the settings, and air flow measurements and made other calculations.

Indoor air quality encompasses many parameters and pollutants, but this specific focuses on CO_2 levels as a proxy for ventilation effectiveness in ten different cultural centres in Flanders and Brussels. We used our sensor device, the indoor@box, to measure the CO_2 values. These results were linked to other parameters such as actual and maximum occupation of the space, settings of the ventilation system, and air flow measurements and calculations. Combining these different aspects allows us to draw conclusions about the performance of the ventilation systems. Next to discussing the global results, this paper aims to understand how CO_2 measurements during events can be related to the ventilation system, the settings, the nominal capacity and the actual occupancy of the room.

1.1 Previous research

Since 2007, the Department of Environment & Spatial Development of Flanders has been conducting research regarding indoor air quality in homes and schools to give concrete advice to the participants and to inform policy. With the emergence of new technology such as sensors and the ability to transmit more data, the Department of Environment & Spatial Development designed several sensor boxes in 2019 in collaboration with VITO (Flemish Institute for Technological Research) (Lazarov et al., 2019). These sensor boxes, named the indoor@boxes, allow real-time measurements of several indoor air pollutants and components to be transmitted, such as particulate matter (PM), carbon dioxide (CO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), volatile organic compounds (VOC), temperature and relative humidity. Moreover, the indoor@boxes allow for data to be collected over longer periods of time. They are calibrated annually.

As described in previous work the COVID-19 pandemic between 2020 and 2022 generated a big focus in Belgium and in Flanders on CO_2 values and how efficiently ventilation is carried out (De Mulder et al., 2023). The general guideline values during the COVID-19 pandemic were derived from health guidelines: if the CO_2 concentration is below 900 ppm (or not more than 500 ppm higher than the outdoor concentration), we consider the room well ventilated (Taskforce Ventilatie van het coronacommissariaat, 2021). In practice, 900 ppm for an adult engaged in standard light activity corresponds with a ventilation flow rate of 40 m^3/h/person of fresh outdoor air. For values between 900 and 1200 ppm, measures need to be taken to fall back below 900 ppm. Exceedances above 1200 ppm are in principle not allowed and immediate action or evacuation is required to improve the CO_2 concentration. CO_2 values are considered a good proxy to monitor the quality of the indoor air, the ventilation and aeration, and an important preventive measure to limit potential contamination via airborne transmission of viruses. The guidelines of 900 ppm and 1200 ppm CO_2 values have been used in our research to get a picture of ventilation performance.

The Department of Environment & Spatial Development has been conducting various measurement campaigns in (semi-)public buildings where many people gather or stay, such as schools, sports centres, residential care centres and cultural centres. The research has resulted in several overarching insights. For instance, ventilation behaviour plays an important role when it comes to indoor air quality. Additionally, the technical aspects of the ventilation are important. While installing the sensor boxes, we noticed that people on site — regardless of the type of sector — often have little knowledge about the presence of a ventilation system, the way it works, or when its last maintenance took place. Based on our findings, we conclude that investing in demand-controlled (mechanical) ventilation — a system that measures and monitors CO_2 values — contributes to improved air quality and consistently lowers CO_2 concentrations in the indoor environment, and therefore helps to reduce airborne viral transmission. But other technical factors of the ventilation also remain important, such as maintenance and proper dimensioning and management of the ventilation system, with an adequate relation to occupancy and activity.

In this paper, we focus on the measurements that were conducted in cultural centres, and more specifically on the relation between the CO_2 measurements during events, the (settings of) ventilation system, and the actual occupancy of the room. This measurement campaign goes further than previous research since a technical screening of the mechanical ventilation system was carried out between two measurement periods. Each cultural centre received a detailed ventilation report with recommendations. The intention was that cultural centres would make certain adjustments based on the screening, and that in the second measurement the effect would be reflected in the CO_2 values. But in practice, we saw that culture centres were unable to adjust their systems in the interim period. Therefore, data from the two measurement periods are analysed together as one dataset. Additionally, data were gathered concerning activities, occupancy and calculated corresponding ventilation flow rate in m^3/h/person and placed into relation with the measured CO_2 concentrations in the indoor air.

2 MATERIALS AND METHOD

2.1 Research in ten cultural centres in Flanders and Brussels

In this paper, we define "cultural centres" as all types of public event buildings where cultural events take place such as theatre, concerts and performing arts. In Flanders and Brussels, most cities or towns have at least one cultural centre. Each of these buildings differ in terms of location, size, venue capacity, age of construction, and type of activities. Almost all cultural centres are polyvalent in terms of activities: music performances (classical, pop, DJ,…), theatre, comedy, exhibitions, cinema, standing or sitting activities, and so on. Often, a cultural centre consists of several halls or event spaces which, again, differ from each other. Globally, there are spaces for performances, for supporting activities (e.g. bar, cloak room, entrance hall,…) and spaces that combine both performance and supporting activities (e.g. bar/foyer, entrance hall/ticket office…). This paper organises in Table 1 the different spaces within the ten cultural centres based on mutual differences and similarities. Table 1 shows (1) the location of the cultural centres[1], (2) the type of space where the measurements took place[2] (3) the type of ventilation system in place in the different spaces, where "no ventilation" means that based on a visual check no natural ventilation system could be detected, (4) the number of activities that took place in the first and second measurement period, (5) the maximum audience capacity of the event space (people sitting (sit.) or standing (st.)), (6) the control of the ventilation system, (7) the efficiency of the air exchange in the different spaces, based on technical measurements and expert technical opinion. This information was synthesized in a descriptive way with two categories "optimal" and "not optimal" and (8) the measured flow rate pulse (m^3/h).

The categorisation of the different spaces where measurements took place are the following: 17 performances spaces, 5 supporting spaces and 4 spaces that combined performance and supporting activities. 17 spaces have a mechanically balanced ventilation system, a mechanical ventilation system or a system with mechanical extraction (predominantly with timer control). For 5 spaces it was unknown whether ventilation systems were present. Additionally, there are 4 spaces where there was no mechanical ventilation system present, and one performance space with no ventilation system.

The indoor@boxes were used for two measurement periods, each time for approximately two weeks: once during May and June, and once during October, November and December 2022. In total, we measured the CO_2 levels during approximately 290 events. In-between these two measurement periods, the spaces with mechanical ventilation were screened for the ventilation systems' characteristics and air flow rate, e.g. control of the ventilation system according to EN 13779:2004, measured flow rate pulse in m^3/h fresh air according to NBN EN 12792, NBN EN 13779 and EN12599 for ventilation duct measurement and an assessment of the efficiency of air exchange based on the location of pulsion and extraction points. It is important to note that this research's sample of buildings and performance spaces is too small to make generalisations for all cultural event centres in Flanders and Brussels. Nevertheless, the data suffice to formulate several descriptive statements.

Table 1: Main characteristics of the cultural centres, the spaces and the ventilation types.

(1) Location cult. centre	**(2) Type of space in cultural centre**	**(3) Ventilation system of space**	**(4) No. activities (period 1 + 2)**	**(5) Max. capacity people**	**(6) Control of vent. System**	**(7) Efficiency of air exchange**	**(8) Measured flow rate pulse (m^3/h)**
1. Capital	1. Perform.	Mech. bal.	11 + 11	1000 / 2000	Timer control	Not optimal	62336
	2. Perform.	Mech. bal.	4 + 5	100 / 300	Timer contr.	Not optimal	13316
	3. Combi.	Mech. bal.	11 + 11	NA	Timer contr.	Not optimal	6375
2. Town	1. Perform.	Mech. bal.	2 + 8	428 sit.	Manual	Optimal	1752
	2. Support.	NA	2 + 8	NA	NA	NA	NA
3. Town	1.Perform.	Mech. bal.	2 + 10	329 sit.	Timer contr.	Optimal	4640
	2. Support.	NA	3 + 10	NA	NA	NA	NA
4. Town	1.Perform.	Mech. bal.	7 + 9	402 sit.	Timer contr.	Not optimal	14971
	2. Support.	NA	7 + 9	NA	NA	NA	NA
5. City	1. Perform.	Mech. bal.	3 + 14	290 / 670	Timer contr.	Not optimal	13876
	2. Combi.	Mech. bal.	3 + 4	150 st.	Timer contr.	NA	1124
6. City	1. Perform.	Mech. bal.	4 + 8	288 sit.	Timer contr.	NA	11041

[1] Cities are defined as urban areas with more than 50000 inhabitants and towns as urban areas with more than 5000 inhabitants in 2019

[2] Additional information about the volume of the space has been considered, but is not required, as the Flemish policy is based on CO_2 values per person.

	2. Perform.	Mech. bal.	4 + 16	940 sit.	Timer contr.	NA	25756
	3. Combi.	Mech. extr.	5 + 12	NA	Timer contr.	NA	NA
	4. Perform.	Mech. bal.	3 + 9	803 sit.	Timer & direct	NA	24514
7. Town	1. Support.	Mech. bal.	1	NA	Timer contr.	NA	2251
	2. Perform.	No mech. ventilation	2 + 3	144 sit.	NA*[3]	NA*	NA
	3. Combi.	No mech. ventilation	1	NA	NA*	NA*	NA
8. Town	1. Perform.	Mech. bal.	2 + 5	480 st.	Manual	Optimal	8791
	2. Perform.	No vent.	2 + 5	391 sit.	NA*	NA*	NA
9. City	1. Perform.	Mech. bal.	3 + 9	127 sit.	Direct cont.	Optimal	5091
	2. Support.	No mech. ventilation	4 + 4	NA	NA*	NA*	NA
	3. Perform.	No mech. ventilation	6 + 3	130 sit.	NA*	NA*	NA
10. City	1. Perform.	Mech. bal.	5 + 4	650 sit.	Direct cont.	Optimal	29794
	2. Perform.	Mech. vent.	2 + 2	400 st.	NA	NA	10950
	3. Perform.	NA	4[4]	200 sit.	NA	NA	NA

2.2 Measurements indoor@box: ventilation efficiency using CO_2 levels

For the research in cultural centres, the indoor@box was used. Although the box can monitor different pollutants, only the CO_2 measurement results were used. The assumption is that the higher the CO_2 concentration, the higher the concentration of bioaerosols (microdroplets produced by breathing) that can contain microorganisms such as bacteria and viruses, that can spread via airborne transmission in addition to contact transmission and droplet transmission. Additionally, CO_2 concentration is a good indicator of the efficiency of ventilation and aeration in function of its occupancy (Geyskens & Stranger, 2016).

One or more indoor@boxes were placed in the different spaces of the ten cultural centres. The indoor@box transmits an interval measurement of the CO_2 concentration every three minutes to the data platform where they are available for analysis. The platform also allows real-time monitoring of the measurements to intervene, if necessary, when the CO_2 concentration becomes too high. Measurements by the boxes provide data points that can be checked against the guidelines of 900 and 1.200 ppm. If, during an event, CO_2 concentration exceeds 900 ppm (or 500 ppm above outside air concentration), ventilation capacity as delivered at that time is insufficient given the current occupancy and action is required. Concentrations above 1.200 ppm are not acceptable from a health perspective. This study reports in what percentage of data points, during events, CO_2 exceeds 900 ppm (Table 2), as well as how many events per space have exceedances of 900 ppm (Table 2).

For the ten cultural centres, additional data has been obtained on the nature of the events, the occupancy (tickets sold), and the start and end time of the event. Unfortunately, not all cultural centres were able to provide this information. However, it is important for the analysis to delineate the duration of the event: at times without spectators, CO_2 levels are low, while during events they evidently rise. For this, an algorithm was used in which all sudden sharp increases in CO_2 concentrations are counted as events, if such increases happen after people enter the venue. The end of the show is defined to be after a significant decrease in

[3] "NA*" stands for "Not Applicable", as it does not concern a mechanical ventilation, whereas "NA" stands for "Not Available". In this case it was not possible to measure the flow rate pulse because the ducts were not accessible or did not exist over enough straight sections.
[4] For that room we only have measurements for the second period, because only then were performances scheduled.

peak values. Each defined start of an event is combined with the consequential end, defined by said decrease in CO_2 values, with a minimum time-limit of 30 minutes, and a maximum of 8 hours. This means that the events reported for the cultural centres in column "No. of activities" of Table 1 do not always fully concur with the events from the algorithm[5].

2.3 Screening of the ventilation infrastructure

In the halls with a mechanical ventilation system, the performance of the system was analysed via air flow measurements (grille and or duct measurements). The mixing section, if installed, was switched off during the measurements, except in performance spaces 6.2 and 6.4, where the mixing section was at 30%. The air groups and how they are operated were analysed. Pulsion, extraction points and energy recovery were mapped for each space partly to assess the efficiency of air exchange, this included regulation by valves. The type of air filtration and the condition of the filters were also assessed. Pulsion and extraction flow rate were also examined to control balance (Table 1). For this study, only the spaces with a mechanical system were screened, as this system defines how the ventilation of the space happens. We only include here the following aspects of the screening for further analysis: the operation of the system, the efficiency of air exchange, and the flow rate.

2.4 Screening of the ventilation effectiveness using flow rate and occupancy

Information was requested from cultural centres on the maximum occupancy of the spaces. The occupancy per activity was also queried in each cultural centre for each space. This information helps to determine whether the ventilation system can provide sufficient flow rate for the nominal capacity (N) and real occupancy of the hall. The measured flow rate of the mechanical ventilation system (Q_{mech} determined in m^3/hr fresh air) was used to calculate, based on both actual and maximum possible occupancy, the flow rate per person (m^3/hr/person). To achieve 900 ppm (N_{900}), a flow rate of 40 m^3/hr/person (V_{900}) is needed for 1.200 ppm (N_{1200}) it becomes 25 m^3/hr/person (V_{1200}), these values are for a MET (activity degree) equal to 1,63 (Taskforce Ventilatie van het coronacommissariaat, 2021):

$$N_{900} = \frac{Q_{mech}}{V_{900}} \text{ or } N_{1200} = \frac{Q_{mech}}{V_{1200}} \quad (1)$$

If these values are not met, then the maximum occupancy possible with the measured ventilation flow rate is determined. In addition, the flow rate necessary to achieve 900 or 1200 ppm with the actual occupancy is determined. The efficiency of air exchange is considered in this analysis.

3 RESULTS

In ten cultural centres, it has been investigated whether (1) each room's ventilation system was technically able to meet the guidelines of 900 and 1200 ppm at full room capacity (calculated with an airflow of 40 m^3/h/pp for 900 ppm, and 25 m^3/h/pp for 1200 ppm), and whether (2) the CO_2 values that were measured with the indoor@boxes during events corresponded with the technical specifications of the ventilation systems.

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[5] A fault margin can occur when, for instance, people enter a room without performances (e.g. for a rehearsal) and cause for the CO_2 to rise significantly. The algorithm will note this as an event. On the other hand, if the ventilation systems work properly during the performance, or if there is a small audience at the event, no significant CO_2 rise occurs. This will not be registered as an event by the algorithm. This fault margin is acceptable as in principle all situations above 900 ppm should be avoided.

Table 2: Main results of the CO_2 measurements, occupancy and ventilation flow rate per space in relation to general health guidelines.

(1) No. space and location	(2) Percentage of time of CO_2>900ppm during events (Min. /Max.), based on indoor@box	(3) Max. audience capacity	(4) Nominal capacity (N900 / N1.200), based on measured flow rate pulse	(5) Sufficient ventilation flow at max. aud. capacity (900 ppm / 1.200 ppm)	(6) Min. amount of people when measured CO_2>900 ppm (events with known occupancy)	(7) Percentage of events with CO_2>900 ppm, based on indoor @box	(8) P1/P99 of CO_2„based on indoor @box
1.1	0 / 74	2000	1558/2493	No / Yes	1312	79	552 / 2940
1.2	0 / 68	300	333 / 533	Yes / Yes	35	31	541 / 1672
1.3	0 / 81	NA	159 / 255	NA	653	96	547 / 2571
2.1	0 / 77	428	394 / 630	No / Yes	151	50	622 / 1182
2.2	0 / 94	NA	NA	NA	NA	54	879 / 1104
3.1	0 / 49	329	116 / 186	No / No	100	60	480 / 1607
3.2	9 / 63	NA	NA	NA	NA	75	524 / 2158
4.1	0 / 100	402	374 / 599	No / Yes	165	73	2463/ 5008
4.2	0 / 98	NA	NA	NA	108	22	723 / 1743
5.1	0 / 73	670	347 / 555	No / No	NA	63	600 / 2008
5.2	4 / 100	150	28 / 45	No / No	NA	100	1361/2832
6.1	0 / 83	288	276 / 442	No / Yes	150	67	781 / 1568
6.2	0 / 53	940	644 / 1030	No / Yes	850	19	560 / 1175
6.3	0 / 34	NA	NA	NA	60	92	519 / 1967
6.4	0 / 0	803	613 / 981	No / Yes	NA	0	566 / 798
7.1	0 / 65	NA	56 / 90	NA	NA	14	634 / 2048
7.2	0 / 54	144	NA	NA	NA	60	502 / 2541
7.3	0 / 76	NA	NA	NA	NA	63	501 / 1355
8.1	3 / 21	480	220 / 352	No / No	85	100	547 / 1098
8.2	20 / 93	391	NA	NA	80	100	848 / 1663
9.1	NA	127	127 / 204	Yes / Yes	NA	NA	NA
9.2	0 / 78	NA	NA	NA	NA	71	710 / 2337
9.3	0 / 84	130	NA	NA	NA	78	751 / 3025
10.1	0 / 75	650	745 / 1192	Yes / Yes	70	80	469 / 1725
10.2	0 / 76	400	274 / 438	No / Yes	200	75	546 / 2451
10.3	0 / 81	200	NA	NA	NA	80	568 / 2399

Table 2 summarizes the main results from the research. The table shows (1) the spaces that have been investigated (for more details see Table 1), (2) the minimum and maximum percentage of time that a measured event exceeded 900 ppm based on indoor@box measurements, (3) the maximum audience capacity, based on the space's design/available space, (4) the maximum (nominal) audience capacity of the space (for 900 and for 1200 ppm), based on the measured flow rate pulse, (5) whether there is sufficient ventilation capacity to ensure CO_2 values below 900 or 1200 ppm when the room is at full capacity, (6) the minimum amount of visitors that were present when an exceedance of 900 ppm was measured during an event (based on events with known capacity), (7) the percentage of events when the indoor@boxes measured CO_2 levels that exceeded 900 ppm and (8) the maximum P1 and P99 of all the events where the indoor@boxes measured CO_2 values[6]. Based on Table 1, Table 2 and the other gathered and analysed data, we summarise the findings in 3 points, using specific spaces as illustrations.

[6] We choose P1 and P99 because maximum values matter in this study, but we still want to exclude certain anomalies in the data (e.g. someone coughing on the sensor).

3.1 Global CO_2 results compared to the general health guidelines

When looking at all the measured events in all cultural centres, some insights can be gathered. With the exception of one performance space (6.4)[7], all performance spaces had CO_2 exceedances of the 900 ppm threshold during at least one event. The threshold of 900 ppm in the CO_2 levels has been exceeded during 68% of the measured events. The highest value that has been measured during an event is 5046 ppm. The measurements show that, on average, the CO_2 values in an event space exceed 900 ppm between 1 and 70% of the duration of the event, with several events that have exceedances during more than 90% of the time. Most measured events significantly exceeded general health (and COVID-19 pandemic guidelines).

3.2 Ventilation at full audience capacity

For 14 of the measured spaces, enough data were available to calculate whether the flow rate pulse of the ventilation system that is present would (theoretically) suffice when the space is at full audience capacity. To ensure CO_2 values below 900 ppm at full audience capacity, only 3 spaces (performance spaces 1.2, 9.1, and 10.1) turned out to have sufficient ventilation capacity. This means that in almost 80% of the cases, the ventilation system is under-dimensioned or uncapable to keep CO_2 values below 900 ppm at full audience capacity. In these cases, the maximum audience capacity of the performance spaces is between 4% and 65% higher than the ventilation system would allow, with a peak of 81% (performance space 5.2). To ensure CO_2 values that remain below 1200 ppm, the ventilation systems of 10 performance spaces suffice. In the remaining 4 spaces, where the dimensioning of the ventilation system cannot guarantee values below 1200 ppm, a serious under dimensioning or a measured flow rate that is too low can often be seen, where an additional 17% to 70% of air flow will be needed before meeting the 1200 ppm threshold. Some spaces also have an over dimensioned ventilation system, with numbers that range from 4% (performance space 6.1), to 11% (performance space 1.2) and 13% (performance space 10.1) additional capacity of air flow. One room (performance space 9.1) has a ventilation system that is perfectly dimensioned for its maximum audience capacity.

3.3 Ventilation systems linked to audience capacity and CO_2 results

One of the initial hypotheses of this research was that the results of the CO_2 measurements during events would be directly related to the ventilation system, the settings and the actual occupancy of the room. In practice, CO_2 values turned out to be the result of a more complex interplay of numerous factors, some of which were not always clear. This complexity can be illustrated by some examples. Our sample size of event spaces with well-dimensioned ventilation systems is quite small (4 spaces): the analysis does not allow for generalisations. However, it is notable that none of these rooms were able to keep CO_2 values below 900 ppm during events. Technical aspects such as efficiency of air exchange play a role, as does the type of activity and the engagement of the public. Performance space 1.2, for instance, theoretically has a proper dimensioning of its ventilation system to keep CO_2 values below 900 ppm at full capacity. With a maximum capacity of 300 people for the room, and a nominal capacity of 333 people to remain under 900 ppm based on the ventilation system, there is an over dimensioning of 11%. For the CO_2 values to remain under 1200 ppm, the over dimensioning is even 78%. However, during the two measuring periods in this performance space, 31% of the events exceeded the threshold of 900 ppm between 5 and 68% of their

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[7] This can be explained because the maximum capacity was not reached: there was only an audience of 400 people present, while there is space for 803 people.

duration. Exceedances of 900 ppm were already measured with an audience of only 35 people. These results may be explained by the fact that the settings of the ventilation system are not optimal. In terms of efficiency of air exchange, the ventilation system is not optimal (see Table 1).

Another example of theoretically good dimensioning of the ventilation system is performance space 10.1. With a maximum audience capacity of 650 and a nominal capacity of 745 to stay below 900 ppm CO_2 values, there is an oversizing of 13%. During the measurement periods, with about 635 tickets sold, the performance space was almost at maximum capacity, but well below nominal capacity. However, the CO_2 measurements indicate that in 80% of the events there is an exceedance of 900 ppm, varying between 0 and 75% of the event duration. In almost 50% of the events, there are also exceedances of 1200 ppm. Exceedances of 900 ppm happen even at an actual capacity of 70 people. According to the technical data, the ventilation system is optimal in terms of efficiency of air exchange (see Table 1). This is not in line with expectations, which may require further investigation, including regarding the activity degree and the need of fresh air per person.

Out of the 16 performance and combination spaces (with a known mechanical ventilation system), 11 are calculated not to have sufficient flow rate at maximum occupancy for 900 ppm. They are expected to give high CO_2 values for longer periods of times at high room occupancy. Overall, this seems to be the case, 3 performance and combination spaces (5.2, 8.1, 8.2) have exceedances of the 900-ppm limit at 100% of their events, and 6 spaces (1.3, 4.1, 5.2, 8.2, 9.3, 10.3) have at least one event with more than 80% of the event duration exceeding 900 ppm. Three spaces, which perform better than the others are worth discussing briefly. The first performance space, 6.2, has a mechanically balanced ventilation system, a maximum seating capacity of 940 and a nominal capacity of 644. Unfortunately, there are no technical data about the efficiency of air exchange for this space. During the measurement periods, several events were fully booked. However, it is only at a capacity of 850 people that exceedances of the 900-ppm value were noted. So, although the ventilation system does not perform at maximum capacity of 940 people, it seems that the ventilation system is self-adjusting according to the audience occupancy. Technical screening of the ventilation system and CO_2 measurements seem to complement each other, to get a good grasp of the ventilation performance. The second performance space is 6.4, which is already discussed briefly. It is equipped with a mechanically balanced ventilation system and is the only performance space without exceedances of the 900-ppm level. This is probably due to the lack of audience: this space has a capacity of 803 people, and a nominal capacity of 613, but during the measurement periods, only a maximal of 400 tickets per event were sold. However, it shows that a reduced capacity of audience can, in certain cases, be beneficial for the CO_2 levels. This finding contrasts with previous paragraph where some spaces still had exceedances of the CO_2 levels, even when maximum capacity is not reached. At last, the third performance space (8.1) has a mechanically balanced ventilation system and shows exceedances of 900 ppm CO_2 level at all events, but only for a short amount of time (only 3-21% of the events duration), which is, compared to the other spaces, remarkably shorter. This suggests that the ventilation system only kicks in after some time. It is worth noting though, that this space was not at maximal capacity with only 85 people playing brass instruments, while the maximum capacity is 480 and the nominal capacity 220.

4 CONCLUSIONS

In general, the research has shown that most cultural centres struggle to meet the general health guidelines to maintain CO_2 concentrations below 900 ppm. Even when the maximum audience capacity of the space is not met, the guideline of 900 ppm is often exceeded. This means that there is clearly room for improvement when it comes to ventilation performance. Each cultural house received an individual report with recommendations from the study, which they can take further.

Measuring CO_2 values remains a good and easy indicator to determine whether an event space is adequately ventilated. Especially if you consider that in cultural centres the intensity of the activity, the composition of the audience (children/adults, sitting/standing) can vary greatly. This research simultaneously showed that having a ventilation system with sufficient flow rate pulse, in relation to the maximum capacity of the room does not always guarantee desirable CO_2 values. Additional parameters that can have an influence — and therefore should not be neglected — are, for instance, the settings of the ventilation system, the intensity of the activity in the room, the composition of the audience, the maintenance of the system, and so on. One aspect to investigate further is determining the activity degree and the need of fresh air per person.

To determine whether a ventilation system is performing properly, the screening of the ventilation infrastructure offers great added value. Several parameters determine the proper performance: installation and setting (e.g. flow rate pulse), correct use and maintenance. A screening identifies these parameters and concrete improvements can be made where necessary (e.g. maintenance of ventilation grids). In the next step, the findings from this research could summarised and incorporated into technical guidelines. The results will be shared with all policy levels as a basis for policy development too.

5 ACKNOWLEDGEMENTS

We wish to thank Joris Pieters, data scientist at Keyrus, warmly for his help with data analysis, the engineering office AirX, for the technical screenings, and the ten participating cultural centres.

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